On the Structure of Broadened Spectrum Lines.

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[PLATE 4.]

In a recent paper, Lord Rayleigh* has discussed the causes which determine the widths of spectrum lines, and which he summarises as follows:—

(i) The translatory motion of the radiating particles in the line of sight, operating in accordance with Doppler's principle.

(ii) A possible effect of the rotation of the particles.

(iii) Disturbance depending on collision with other particles either of the same or of another kind.

(iv) Gradual dying down of the luminous vibrations as energy is radiated away.

(v) Complications arising from the multiplicity of sources in the line of sight.

Of these (ii) does not in fact occur, and (v), which is not an independent cause of broadening but merely aggravates other causes, need not be considered in the present communication.

It is shown that in vacuum tubes at low pressures, excited by uncondensed discharges, (i) is the important effect, and in fact completely accounts for the widths of the lines. Under these conditions, the limiting order at which interference can be seen is given by the equation $N = K\sqrt{(M/T)}$, where N is the limiting order of interference, M the mass of the luminous particle in terms of the mass of the hydrogen atom, T the absolute temperature, and K a constant, the exact value of which depends on an estimate of the smallest value of the "visibility" for which interference fringes can be recognised, the visibility V being defined by the equation $V = (I_1 - I_2)/(I_1 + I_2)$, where I_1 is the intensity of light at the maxima and I_2 at the minima. Thus Lord Rayleigh gives $K = 1{\cdot}427 \times 10^6$, this value being based on experiments made with fringes, produced by means of double refraction, which could be perfectly controlled. Buisson and Fabry† adopt the value $K = 1{\cdot}22 \times 10^6$, based on a higher estimate for the limiting value of V.

The equation $N = K\sqrt{(M/T)}$ has been experimentally verified by Buisson and Fabry (*loc. cit.*) for vacuum tubes at low pressures when excited by

* 'Phil. Mag.,' vol. 29, p. 274 (1915).

† 'Journ. de Physique,' vol. 2, p. 442 (1912).

uncondensed discharges, and they have also shown that the temperature of the luminous gas is that of the tube or not much higher, as originally assumed by Michelson.

The widening of spectrum lines which occurs at higher pressures cannot be said to rest on a secure theoretical basis. It has been assumed that this widening is due to collisions of the luminous particle with other atoms, on the supposition that the length of the wave train is limited by the interval between the collisions, though, as Lord Rayleigh points out, this treatment is far from complete, since it assumes that an entirely fresh start is made at each collision and "there must surely be encounters of a milder kind where the free vibrations are influenced, but yet not in such a degree that the vibrations after the encounter have no relations to the previous ones."

An important case of broadening is that which occurs when condensed discharges are used. Widening of this type is very marked in the Balmer series of hydrogen, and to a somewhat smaller extent in the ordinary helium spectrum, and is especially prominent in the case of lines of the "spark" type, such as the "4686" line of helium. The magnitude of the widening in vacuum tubes depends to a great extent upon the pressure of the gas in the tube and is not conspicuous at very low pressures. It is well known, however, that in hydrogen tubes at high pressures, excited by heavy condensed discharges, the lines widen until they become scarcely recognisable.

I have investigated the effect of condensed discharges on helium and hydrogen at pressures of about a millimetre by means of a Fabry and Perot interferometer. The apparatus and method have been described in a previous paper.* The numerical results of this investigation are not considered to be of quantitative interest, for reasons to be given later, but the main results which are in agreement with those of other investigators, may be stated.

(i) Whilst with uncondensed discharges the limiting order of interference N is constant for different lines belonging to the same element, this is no longer the case when condensed discharges are employed.

(ii) For a given series the value of N becomes less as the series number of the line increases, that is to say the more refrangible lines undergo the greatest broadening.

(iii) Different series are affected to a different degree.

(iv) The magnitude of the broadening decreases as the pressure decreases.

We may draw certain conclusions as to the possible origin of the broadening. In the first place, it is evidently not due to a rise of temperature at each impulse of the condensed discharge. From the equation $N = K\sqrt{(M/T)}$, we see that a rise of temperature would lower the value

* 'Roy. Soc. Proc.,' A, vol. 91, p. 421 (1915).

of N, but that the value of N should remain constant for all the lines, which in fact does not occur.

Bohr* has suggested that the breadth of the spark line of helium at $\lambda = 4686$ Å.U. may be due to the charge carried by the luminous particles, in virtue of which they must be expected to acquire high velocities in the electric field of the discharge tube. Such an effect must be expected to occur in all cases in which the luminous particles are electrically charged. With vacuum tubes excited by uncondensed discharges, it certainly does not occur, or is negligibly small, since Buisson and Fabry (*loc. cit.*) have shown that the temperature of the luminous gas calculated from the limiting order of interference gives a value little different from that of the walls of the tube, and the effect suggested by Bohr would simply be equivalent to an increase in the value of T in the equation. In any case the effect should consist of a uniform lowering of the value of N throughout the spectrum, which is not in accordance with observation. Thus, while some broadening of the lines is to be expected if the luminous particles carry an electric charge, it does not appear to be important or to offer in any way a satisfactory explanation of the experimental results. One may, indeed, question whether, under the conditions ordinarily obtaining in vacuum tubes, any considerable proportion of the luminous particles do carry an electric charge. It is difficult otherwise to explain the failure of numerous investigators to detect any Doppler effect in an end-on vacuum tube when the direction of the current is reversed. It would thus appear doubtful whether the broadening produced by condensed discharges can be due to the movement of the luminous particle as a whole, but rather that it must be referred to processes more intimately connected with the problem of radiation.

Stark† has suggested that the broadening is intimately connected with the electrical resolution of spectrum lines, being in fact due to the influence of the electrical field of neighbouring particles on the luminous atom. Stark points out that the electrical resolution of lines of a series increases with the term-number, and that the broadening increases in a similar manner; also that lines in the spectra of helium and lithium, which show an asymmetrical broadening, are also asymmetrically resolved by the electric field. Though little is known of the potential gradients which occur when a vacuum tube is excited by condensed discharges, it seems improbable that the potential fall in the capillary of the tube would be great enough to give rise to any considerable broadening.

I have made the following experiment, which would appear to show that

* 'Phil. Mag.,' vol. 30, p. 401 (1915).

† 'Elektrische Spektralanalyse Chemischer Atome,' 1914.

no appreciable broadening is due to the field of the tube. It is evident that with a condensed discharge the separation of the outer components D, due to the electric field of the discharge tube, will oscillate between $D = 0$ and $D = f(V)$, where V is the maximum value to which the potential gradient rises, the result being a broadening of the lines. Now Stark has shown that the hydrogen line H_α examined in a direction perpendicular to the electric field is resolved into three components, the outer components being polarised at right angles to the centre component, which is coincident in wave-length with the unresolved line. If, therefore, the outer components are cut out by means of a Nicol prism, the line should appear to become narrower. A vacuum tube containing hydrogen was excited by an uncondensed discharge, and the line H_α was examined with a Fabry and Perot interferometer, the plates of which were set at a distance such that the fringes were distinctly visible. On exciting the tube with a feebly condensed discharge all trace of interference vanished. By reducing the distance between the plates the fringes could be made visible again. A Nicol prism was interposed and slowly rotated whilst the observations were being made, but under no conditions could any change in the width of the line be detected. It would, therefore, appear that the effect due to the field of the discharge tube is negligible, but rather that the broadening is due to the electric field of neighbouring particles, as assumed by Stark. In accordance with this is the fact that the mean distance between the particles will be diminished by an increase of pressure, also an increase in the number of charged particles will result from the considerable current density which obtains when condensed discharges are employed, both these circumstances giving rise to a broadening of the spectrum lines.

We may now consider the distribution of intensity to be expected, on the above view, when the hydrogen lines are broadened. It is evident that the effects due to electric fields perpendicular to and along the line of sight will be superposed. In the former case (the transverse effect), there are components polarised parallel to the field (*p* components) and other components polarised perpendicular to the field (*s* components). In the latter case (the longitudinal effect), the components are unpolarised and agree in position and relative intensity with the *s* components of the transverse effect. Fig. 1 shows the electrical resolution of the three lines H_α, H_β, and H_γ, the relative intensities being denoted by the diameters of the circles. It may probably be assumed without serious error that the total intensity of light emitted in the longitudinal effect is equal to twice the total intensity of the *s* components of the transverse effect. To obtain the resultant of all the superposed effects, it is therefore necessary to combine

the p and s components of the transverse effect, increasing the intensities of the s components threefold to provide for the longitudinal effect. Now if the mean value of the electric field is V, there will be a maximum in the

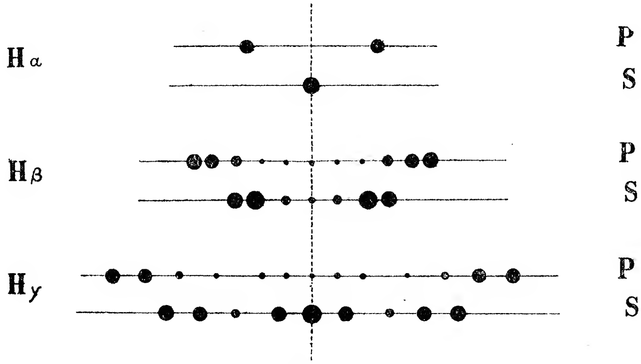


Fig. 1.

intensity distribution curve corresponding to the electrical resolution of each component by an electric field V, these points being the maxima of curves relating the displacements corresponding to a certain electric field to the number of particles subject to a field of that magnitude. The undisplaced central components of H_α and H_γ will remain as narrow lines, whilst the displaced components will be spread out, the lines thus having a strong central core with nebulous wings depending on the mean intensity of the field, the winged effect being much more pronounced in H_γ than H_α, since the electrical resolution of the latter is much smaller. The case of H_β is different. The central undisplaced component of this line is feeble in comparison with the displaced components, and there should, in consequence, be a minimum of intensity in the centre of the broadened line.

An attempt has been made to study the distribution of light in the three lines considered, whereby these views may be put to an experimental test.

It is at once evident that observations with the interferometer are of no value for this purpose. The interpretation of the limiting difference of path at which interference phenomena can be seen depends on a previous knowledge of the intensity distribution, and the use of the interferometer is therefore restricted to cases in which the intensity distribution can be predicted.

The structure of spectrum lines photographed under a high dispersion has recently been investigated by King and Koch,* whose method consists in a measurement of the degree of blackening of the photographic plate at different points on the broadened line, this being accomplished by means of an

* 'Astrophys. Journ.,' vol. 41, p. 214 (1914).

ingenious automatic device for recording continuously the density of the plate at different wave-lengths. Methods of this type have yielded valuable information of the asymmetry of lines under different conditions, but they would appear to be vitiated by the eccentricities of the photographic plate, the most important of which is that the degree of blackening is not proportional to the intensity of the light. It is thus difficult to attach any quantitative meaning to the curves obtained in this way.

In the present investigation a method has been adopted, by means of which it is believed that an accurate quantitative measurement of the intensity distribution in spectrum lines can be made, and the qualitative structure of broadened lines can at once be seen.

The method consists of an application of the neutral-tinted wedge method which is used for recording the sensibility curves of photographic plates. A neutral-tinted wedge of density graded from 0·2 to 4·2 was mounted vertically on the slit of a spectrograph and the slit was illuminated with light from the source to be studied, care being taken, before the wedge was put into position, that the required length of the slit was evenly illuminated. Under these conditions the spectrum appears to consist of lines, bright at the points corresponding to the thin end of the wedge, and gradually fading off with increased density. It is evident that, from the apparent lengths of two lines, their relative intensities can be calculated, provided that they are so close together that errors due to the variation of the sensibility of the plate to different wave-lengths do not arise. A broadened line gives a wedge-shaped image on the plate, the apex corresponding to the maximum of intensity in the line, and, from the shape of these wedges, the intensity at different distances from the maximum can be calculated. It will be seen that the method consists in picking out points of equal density at different wave-lengths and determining the thicknesses of the wedge to which they correspond. Points of equal density must indicate equal illumination, since they are exposed for the same time and subjected to the same treatment. The method is thus unaffected by the eccentricities of the photographic plate, and it is only necessary to assume that there is one particular density that can be recognised at different points.

For the investigation of the hydrogen lines, which were produced by the passage of condensed sparks through hydrogen at atmospheric pressure, the dispersion of a single-prism spectrograph was sufficient, and the neutral wedge was mounted in front of the slit as described above. A number of plates were taken, and the results were also confirmed by visual observations. In Plate 4 is shown an enlargement of a photograph obtained in this way. It is doubtful whether the detailed structure can be seen, but, in

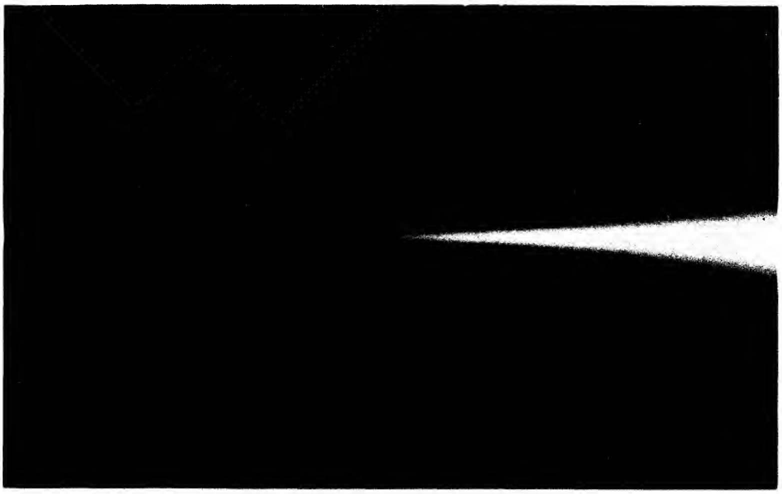
all the original negatives, certain outstanding features were evident. H_α consisted of strong maximum, falling off rather rapidly, and apparently regularly.* In H_β the intensity falls off much less rapidly, and there is a distinct minimum at the centre of the line, which appears to be a hazy doublet. H_γ has a bright central line with very wide nebulous wings. This appearance of H_γ has been previously noted by Rossi,† and Prof. Fowler has informed me that the appearance of H_β, with a minimum at the centre, is familiar to him. The essential point would appear to be the different behaviour of the three lines produced under identical conditions. It may be regarded as extremely improbable that the minimum in H_β is due to reversal, for in this case one would expect, *a priori*, that the effect would be more strongly marked in either H_α or H_γ.

The observed effects appear to be in close agreement (at least qualitatively) with the intensity distribution deduced from Stark's observations of the electrical resolution of the lines, and the results would appear to support strongly Stark's view that the broadening of spectrum lines at high pressures and under conditions of powerful excitation is due to the resolution of the lines by the electric field of neighbouring atoms.

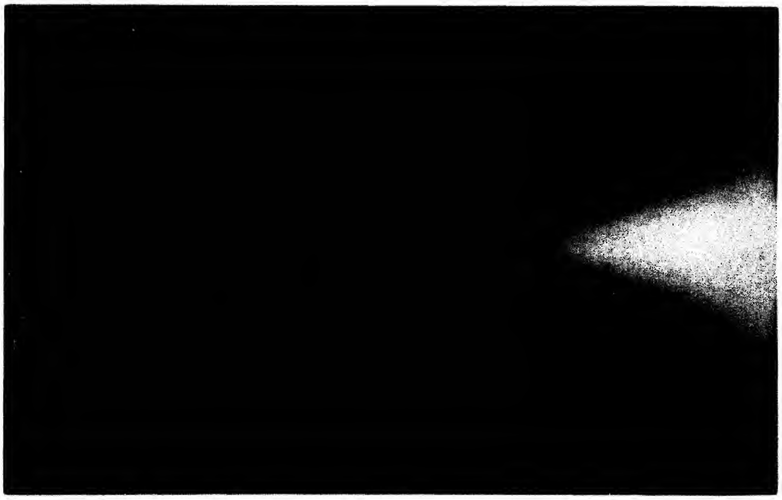
In this paper the exact shape of the curves obtained has not been discussed. Quantitative measurements, with improved experimental arrangements, are now in progress, and it is hoped that material will be obtained for a theoretical investigation of the distribution curves, but, in view of the time which these investigations will occupy owing to pressure of other work, it was thought that the results given above might be of sufficient interest for separate publication.

* It will be observed that the image of H_α shows some solarisation. This is easily distinguished from true doubling or reversal by the fact that it is most conspicuous at the base of the wedge and does not extend to the apex, whereas true doubling or reversal appears at the apex and becomes less conspicuous towards the base.

† 'Astrophys. Journ.,' vol. 41, p. 232 (1914).

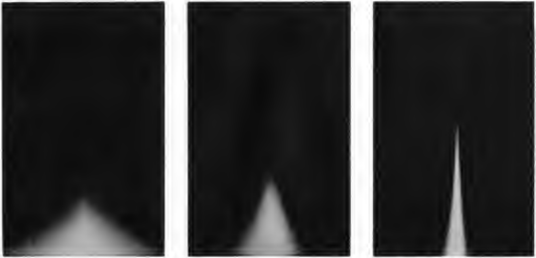


Hα



Hβ

Hγ



$H\gamma$ $H\beta$ $H\alpha$